Adhikari *et al. Biochar* (2025) 7:89
https://doi.org/10.1007/s42773-025-00480-0

Biochar

ORIGINAL RESEARCH

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Optimizing sustainable basil cultivation with smart-monitoring: a comparative study of biochar and soilless growth media

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Abstract

This study evaluated the efficiency of different soilless growth media for sustainable basil cultivation compared to traditional potting mix with continuous monitoring. This paper presents a novel approach of continuous physico-chemical monitoring of basil growth using Internet of Things (IoT) enabled smart growth cabinets. Six growth media combinations—sand, coir, and biochar (unsoaked and nutrient-enriched), sand, coir, and perlite, and potting mix with 10% and 20% biochar—were tested over 30 days under controlled conditions, with potting mix as the control. The pH, electrical conductivity and cation exchange capacity of growth mixes were analyzed before and after, along with key growth metrics such as root length, shoot length, leaf number, fresh and dry plant weight and leaf area index (LAI) were analysed. Results indicated that incorporating 10 to 20% biochar into potting mix optimally enhanced basil growth, with significant improvements in root development and the LAI of the plant. Biochar soaked in nutrient solution demonstrated three times higher plant weight compared to unsoaked biochar, indicating the potential of biochar as a slow-release nutrient matrix. Despite the high exchangeable potassium and sodium of biochar, calcium and magnesium remained dominant in the potting mix, indicating the need for optimising biochar use as a horticultural growth media according to the plant type chosen. Replacement of 10 to 20% of potting mix by biochar supports the circular economy goals by enhancing plant growth and sequestering carbon.

Abstract Highlights

- Continuous IoT enhanced monitoring within a smart cabinet enabled successful horticultural growth trials within 30 days.
- Biochar treated with nutrient solution increased plant weight by three times compared to untreated biochar.
- Replacement of 10–20% of potting mix with biochar increased the potassium content by three times and increased root length of basil.

Keywords Protected cropping, Potting mix, Replacement, Sustainable horticulture, IoT

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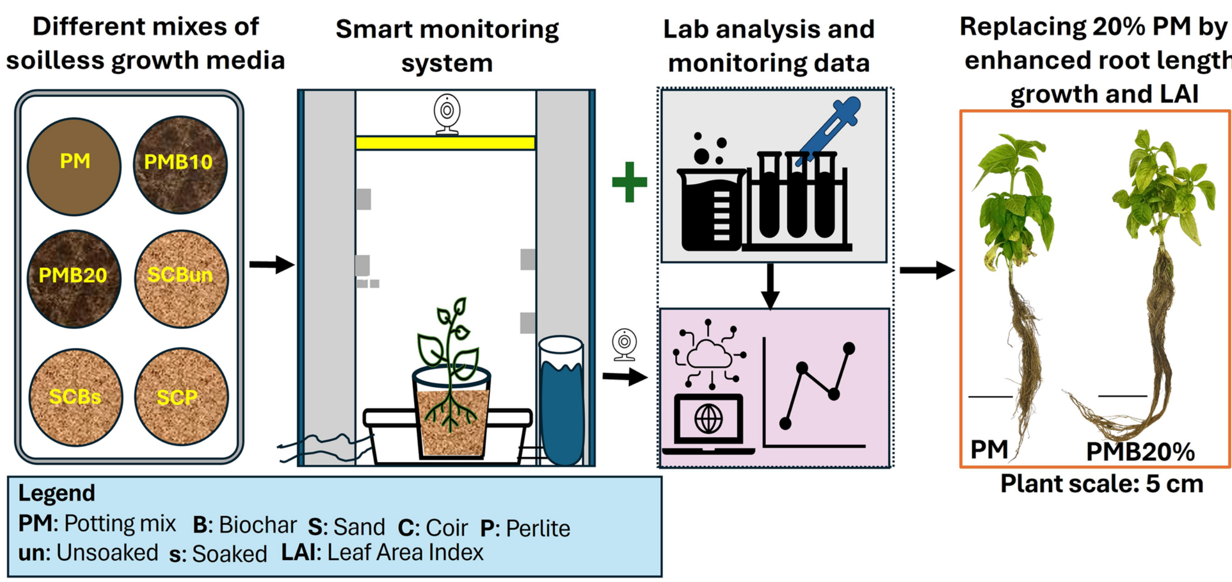
Graphical Abstract



1 Introduction

Sustainable horticulture is increasingly needed to address the challenges posed to food security by the increase in food and plant demand due to population increase, resource limitations and climate change (Kaushal et al. 2024). Traditional farming methods are often hindered by soil degradation, nutrient depletion, and inefficiency in water usage. In this context, soilless growth media, particularly those incorporating biochar, offer a promising solution for enhancing crop productivity while minimizing environmental impact (Chopra et al. 2024; Kumar and Verma 2024). These systems not only reduce reliance on natural soil but also allow for improved control over nutrient and water supply, making them essential for future farming systems (Kaushal et al. 2024; Sharma et al. 2024).

The use of soilless growth media is gaining attention, particularly when traditional soil is substituted by alternative materials such as horticultural sand, coconut coir, potting mix, biochar, perlite, or mixtures of these components (Khomami et al. 2024; Rathnayake et al. 2021). For example, sand is often employed as a growing medium for plants requiring well-drained environments, as excessive water produces runoff rather than being retained, unlike in clay-based soils (Hussain et al. 2014). Coconut coir, marketed under various names such as ultra peat and cocopeat, offers excellent water retention combined with good air permeability, making it a popular organic medium (Khomami et al. 2024). Derived from shredded coconut husks, it not only protects seeds but also promotes rooting and germination by providing a fungus-free, hormone-rich environment (Ajien et al. 2023). Unlike peat moss, which faces depletion due to overuse, coconut coir is a renewable resource. Perlite is deemed beneficial for its water and air holding capacity due to its high porosity; however negligible effect on nutrient composition of growth media and plant nutrient uptake has been reported (Kingston et al. 2020). Perlite maintains the density of the substrate even over time as compaction of other media such as peat and potting mix occurs (Burdina and Priss 2016). Therefore, addition of perlite is reported to enhance the root growth for basil. Papadimitriou et al. (2024) evaluated the influence of coconut coir and perlite for golden thistle growth and reported that the container height also partly determines plant growth. Water availability, root length, porosity and density are directly related to container height and thus should be considered. In addition, Younis et al. (2022) have identified that larger pore size of the growth matrix including soilless growth media such as sand, coconut coir and perlite facilitates enhanced aeration and water availability, but optimisation for each crop type is necessary.

Recent advances in agricultural technologies, including the integration of Internet of Things (IoT), have provided new tools for optimizing growing conditions by enabling continuous monitoring of plant health and environmental parameters (Ali et al. 2024). Protected cropping systems (e.g. controlled greenhouse environments) equipped with such technologies allow for more accurate and efficient management of soilless media systems, offering further potential for enhancing sustainable farming practices (Rozenstein et al. 2024). A low carbon footprint sustainable agricultural greenhouse has been designed integrating internet of things, sensor networks, minimal use of water resource, and reduction of costs during crop optimisation and harvest (Marouani et al. 2024). Growing conditions such as lighting, humidity, soil moisture, water flow rate were optimised in this hydroponic greenhouse.

Several studies have demonstrated the benefits of biochar in improving plant growth (Chopra et al. 2024; Rathnayake et al. 2021), particularly through its ability to retain nutrients (Adhikari et al. 2024), water holding capacity (Adhikari et al. 2023a; Banitalebi et al. 2021; Méndez et al. 2015), and improved airspace in the growth media (Graber et al. 2010; Tian et al. 2012). Biochar is a porous carbon structure and contains >60% stable carbon that is stable in soil for more than 100 years (Adhikari et al. 2023b). Biochar adds carbon to soil and acts as a slow-release fertiliser (Adhikari et al. 2019, 2024) enhancing nutrient availability to the plants. Short term (up to 3 weeks) benefits of biochar application include the release of dissolved organic carbon and nutrients as well as an increase in electrical conductivity and pH of the biochar soil mixture (Joseph et al. 2021). Biochar increases the soil calcium and reduces Na absorption in loamy soil (Abrol et al. 2016). Similar effect of increase in Ca and reducing Na absorption has been reported when biochar was used in a soilless growth media (Coppa et al. 2024; Mehdizadeh et al. 2019). Early seedling development may be hindered by high concentration of biochar; so careful optimisation is required. Along with biochar concentration, biochar feedstock, production conditions and supporting growth media also impact early development of plants (Joseph et al. 2021). Dissolution of compounds from biochar, free radical movement initiating development of reactive oxygen species, and release of salt from biochar to growth media can influence the chemistry of the growth media, influencing root development in high biochar concentrations (Yu et al. 2019). Biochar enhances photosynthesis, identified by increased photosynthetic pigments in sweet basil (Jabborova et al. 2021) and arrowhead (Zulfiqar et al. 2022, 2019) soilless growth media. Wheat straw biochar increased the number of spikes and number of seeds per spike in wheat cultivation (Kunnen et al. 2024). Biochar amended peat media increased the lettuce germination by more than 100% due to increased air space and water retention (Méndez et al. 2015). Biochar from soft wood at 550 °C has been reported to enhance germination with higher root length and shoot height of common garden cress, lettuce and tomato reduced phytotoxicity (Rathnayake et al. 2021). Similar improvement in plant growth has been observed in other crops such as basil, where application of 3% wt. biochar derived from black cherry wood in sandy soil significantly improved basil plant height, leaf growth, and root development (Jabborova et al. 2021). Additionally, biochar enhances microbial activity, promoting the growth of rhizobacteria and fungi, and contributing to overall plant health through slow release of nutrients for longer term nutrient availability (Graber et al. 2010). Biochar is also reported to enhance the growth of the ornamental plant *Calathea rotundifola* cv. Fasciata. by 22% compared to control peat substrate (Tian et al. 2012) as well as reducing the rate of decomposition of the peat based growth media. In addition, Banitalebi et al. (2024) reported that biochar from wheat straw at pyrolysis temperature of 500 °C has a significant potential to substitute traditional growth media such as coco-peat and perlite for plant growth. Additionally, in another study Banitalebi et al. (2021) reported that biochar derived from date palm at 300 °C and wheat straw at 500 °C can be a suitable replacement for coco-peat-perlite growth media due to its porous nature, enhanced aeration and water retention.

Despite these promising outcomes, research on biochar use in soilless systems has produced inconsistent results, with some studies reporting little benefit or even negative effects on plant growth. Biochar with low density and high porosity is reported to promote biomass growth for basil, whereas an increase in electrical conductivity of biochar decreased growth of basil (Nobile et al. 2020). Vaughn et al. (2013) found that while biochar derived from straw and wood increased plant height of marigold and tomato plants, no effect on dry weight of the tomato was observed. This study identified the influence of application rate of biochar in plant growth and reported that 5% biochar application did not show significant changes, whereas the optimum rate of application was 10 to 15% as shown by this greenhouse experimental setting. Similarly, (Steiner and Harttung 2014) observed no significant growth differences in sunflower plants grown in biochar and peat mixtures (25%, 50% and 75%) wt%, suggesting that high salinity or pH from biochar could cause osmotic stress. This study opened new insights into dealing with highly saline biochar by washing prior to use and environmental and economic benefits of using biochar as a growth medium in different mixes. Other research has highlighted issues such as increased bulk density and reduced plant growth when high ratios of biochar were used in the substrate (Belda et al. 2016; Huang et al. 2019). Belda et al. (2016) explored the use of biochar made from olive mill and forest waste in sandy soil and coconut coir for myrtle and mastic plant growth, finding that the forest waste biochar mixes improved plant dry weight and survival rates, but highlighted the need for optimizing feedstock types and application conditions. Similarly, Huang et al. (2019) assessed the replacement of 60–90% of peat-based commercial substrate with hardwood biochar and chicken manure or vermicompost for basil and tomato growth, reporting reduced plant growth compared to the commercial substrate; however, the mixes maintained similar porosity but showed increased bulk density and air space with over 70% biochar. The study recommended a mix of 5% composted chicken manure, 70% hardwood biochar, and 25% peat, but emphasized the need for further research alternative mixtures to avoid growth impacts of high pH and salt levels.

The discrepancies in previous research highlight the importance of standardizing biochar applications across different growing media. Understanding the specific interactions between biochar, nutrient availability, and plant growth is crucial for developing biochars that can effectively replace less sustainable materials in soilless agriculture. Moreover, integrating real-time data through IoT-based monitoring systems can help track plant growth, moisture, and nutrient levels more accurately, contributing to data-driven decision-making for sustainable farming.

Despite the advances in optimising general physico-chemical properties of the soilless media like coconut coir and sand, significant knowledge gaps remain regarding the interactions of biochar with fertilizers in soilless systems, particularly with respect to nutrient exchange (Ivanova et al. 2023). The formation of aggregates on biochar surfaces, and biological and biochemical interactions, are critical factors influencing plant growth, yet these processes are poorly understood in the context of soilless media (Jabborova et al. 2021). Moreover, the influence of different media composition on plant morphology and growth response has yet to be fully identified. Despite the potential of biochar, its effects in soilless systems (especially for basil) are not fully understood, which hinders the development of optimized growth media. In addition, continuous monitoring incorporating IoT enhances the understanding of potential biochar applications in different soilless systems.

This study leverages IoT-based continuous monitoring systems in controlled greenhouse conditions to examine the interactions between biochar and other growth media on basil growth. Basil (*Ocimum basilicum*) is a widely cultivated herb with significant culinary and economic value. Despite its popularity, optimizing its growth in soilless media with continuous monitoring of plant growth remains a challenge, particularly with respect to nutrient management and media composition. Therefore, the hypothesis of this study is that initial physico-chemical properties of the growing medium, including biochar content, significantly affect basil growth and morphology, and that identifying the optimal nutrient conditions based on exchangeable cations can further enhance growth outcomes. Understanding the application of biochar content and continuously adjusting nutrient conditions will result in optimized plant morphology and nutrient uptake.

This research was designed to meet these knowledge gaps, by addressing three specific objectives. They are (1) to evaluate the influence of initial physico-chemical properties of growing medium for basil over 30 days in a controlled environment, (2) to analyse how basil root length and leaf area respond to various components of growth media including biochar, and (3) to identify optimum nutrient and exchangeable cation conditions in growth media suitable for basil.

2 Methods

2.1 Material sourcing

Biochar provided by a local manufacturer (Green Man Char, Melbourne, Australia) was produced in a continuous pyrolysis plant at temperatures of 500 to 550 °C. Mixed feedstock such as hardwood, softwood, tree residue and garden waste was used to prepare the biochar. Propagation sand, coconut coir and perlite were used to prepare the blends for the experiment with biochar. The pH of the biochar was reported to be 9.98 ± 0.01 and EC of the biochar was reported to be 559.6 ± 3.0 µS cm^{-1} (Adhikari et al. 2022).

Coir, perlite and propagation sand was obtained commercially. The coir used was the Coir Garden Soil Mulch Block (Brunnings Australia, Product ID: 30502), the perlite used was the propagation perlite (Brunnings Australia, Product ID: 3010203) and the sand used was propagation sand (Brunnings Australia, Product ID: 31424).

2.2 Growth media blends

Propagation sand, coconut coir, biochar and perlite were mixed at different ratios to evaluate the efficiency of these mixes in water retention and plant growth compared to the commercial potting mix. The mixture of growth media was filled in 1 L plastic pots, and the basil seedling were planted in a controlled environment, hereafter called as smart growth cabinets. Sand was mixed at 60% v/v with 30% v/v of coconut coir altering with 10 and 20% v/v of biochar. The mix of 30% coconut coir was based on research by Nazari et al. (2011) who found this ratio could enhance water efficiency. Along with that control experiment for potting mix was also done with 100%

Table 1 Growth media blends prepared for the experiments at different percentages by volume

Material (% v/v)	Sample name					
	SCBun	SCBs	SCP	PMB10%	PMB20%	PM
Sand (S)	60	60	60	–	–	–
Coconut-Coir (C)	30	30	30	–	–	–
Biochar (B)	10	10	–	10	20	–
Perlite (P)	–	–	10	–	–	–
Potting mix (Pm)	–	–	–	90	80	100
Hoagland's solution (h)	–	yes	–	–	–	–

The terms "s" and "un" refer to biochar soaked and unsoaked with the Hoagland's solution

potting mix. Details of the mix are provided in the table (Table 1).

2.3 Smart growth system and experiment

The smart growth cabinet refers to a controlled chamber where continuous monitoring of the plants grown within can be achieved with IoT integrated systems. Parameters that can be monitored include light intensity and spectrum, temperature, humidity, barometric pressure as well as RGB images that are taken on a one-hour schedule. To maintain experimental consistency, the basil plants used in this experiment were propagated by rooting stem segments from a single plant under controlled environmental conditions, facilitating the propagation of 18 genetically identical specimens. The experimental matrix in 3 replicates was placed in two trays and kept under controlled greenhouse conditions. The system maintained a temperature of approximately 24 °C and used the Mars Hydro SP3000 light, providing an 18-h light cycle set to an intensity of 280 PAR. This was followed by a 4-h period of darkness where temperatures would drop to approximately 20 °C. The irrigation system utilised a flood and drain system working on a bi-daily watering schedule. A standard hydroponics solution was prepared for the irrigations (Hoagland solution) with macro and micronutrients required for plant growth. The same Hoagland solution was also used to pre-charge selected growth media. The detailed constituents of Hoagland's solution are provided in Appendix 1(A1). The trials were conducted in triplicate for each condition. After 30 days, the basil was harvested, dried at 60 °C for 48 h and analysed and weighed for the above-ground and below-ground biomass (i.e. leaves, roots).

2.4 Physico-chemical analysis of the growth media

2.4.1 pH and EC of the growth media

The electrical conductivity (EC) and pH of the growth media were analysed using 1:5 growth media with some modifications from the method by FAO (2021a, b). The pH and EC of the mixes PM, PMB10%, PMB20% were analysed at 1:5 growth media to water ratio, and for the mixture with sand (SCB10%, SCP10% and SCB10% H) 1:2.5 ratio was used. pH and EC were measured using electrometric method after shaking the mixture for 1 h continuously in a magnetic stirrer and left for 1 h to decant before analysis (Singh et al. 2017). pH and EC of individual components of the growth media (sand, coconut-coir, biochar, perlite, and potting mix) were also evaluated using this method. The pH and EC were analysed during the start of the experiment, after 14 days and at the end of the experiment (30 days).

2.4.2 Cation exchange capacity (CEC) of the growth media

The CEC of the growth media was reported as the sum of the base cations displaced by 1 M ammonium acetate NH_4OAc using the modified method by Adhikari et al. (2024). The required apparatus was acid cleaned using 10% nitric acid (HNO_3), rinsed thoroughly with deionised water, and dried at 105 °C overnight. Approximately ~ 1 ± 0.05 g of the oven dried growth media at 105 °C for 18 h was placed in a 100 ml falcon tube with 20 ml of deionised water. The pH of the sample was adjusted to 7 if it was alkaline by adding 0.05M HCL and the EC was brought to < 200 µS cm^{-1} by washing (shaking, centrifuging, and decanting) it until the EC reached the required number. Finally, the sample was mixed with NH_4OAc in an orbital shaker for 18 h and filtered using 0.45 µm filter paper to obtain the filtrate for analysis of cations Ca^{2+}, Mg^{2+}, and K^+ using Inductively Coupled Plasma Optical Emission Spectroscopy ICP-OES (Agilent 5900 SVDV smart ICP system).

2.5 Biomass analysis of basil harvest

After 30 days, plant height, leaf length, leaf number, root length, fresh and dry root weight and fresh and dry shoot weight were measured after harvest.

2.5.1 Continuous monitoring of Leaf Area Index

Continuous monitoring of plant growth was enabled by a high-definition RGB camera positioned approximately 2 m above the plant canopy in the cabinet's centre, capturing an image every hour. The final images were pre-filtered to remove any photos captured while the lights were off. The remaining images were then processed using an AI system designed to create masks with limited training datasets. The Leaf Area Index (LAI) was calculated in pixels from these images.

To reduce noise between images, a Locally Weighted Scatterplot Smoothing (LOWESS) filter was applied to each of the plant LAIs over time, with a fraction parameter of 0.1 used. The resulting average of the triplicates for each condition was also plotted over time and used to calculate the growth rate, which has been expressed as a function of growth over time using the following formula:

$$Total\ Change(\%) = \frac{Final\ LAI - Initial\ LAI}{Initial\ LAI} \times 100$$

The average of the triplicate plants was also used to determine the daily growth rate expressed as a percentage comparing total change over days:

$$Average\ Daily\ Growth\ Rate(\%) = \frac{Total\ Change(\%)}{Number\ of\ Days}$$

3 Results and discussion

Table 2 presents a snapshot of the key growth parameters and media characteristics observed in this study. The data show variations in plant growth metrics, LAI measurements, and exchangeable cation concentrations across the different growth media formulations.

3.1 Influence of physicochemical properties of growth media

The physicochemical properties such as pH and EC of all growth mixes were calculated before planting and after harvest. The changes in the pH and EC and how they relate to growth are discussed in the section below.

3.1.1 pH and EC

It was observed that lower pH up to 7.5 and high EC up to 1200 µS cm^{-1} facilitate the effective growth of basil. The potting mix as a control showed ideal conditions for growth of basil with a daily growth rate of around 13%. Addition of 20% biochar to potting mix increased pH of the growth media, compared to 10% biochar substitution. However, the replacement of potting mix by 20% biochar showed similar growth rate of 11% and addition of 10% biochar showed a growth rate up to 7% within 30 days (Fig. 1), which can be considered as the moderate use of biochar. The growth rate of basil with 20% of biochar added in the potting mix was similar to that in the potting mix, indicating that the potting mix could be replaced by around 20% biochar without impacting plant growth. Sand, coir and biochar have a higher pH compared to potting mix, ultimately increasing the pH of the

Table 2 Summary of key growth parameters and physicochemical properties of growth media

Growth parameter	PM (control)	PMB10%	PMB20%	SCB10%un	SCB10%s	SCP
Plant growth metrics						
Root length (mm)	253 ± 25	265 ± 62	305 ± 21	194 ± 82	268 ± 44	296 ± 80
Shoot height (mm)	131 ± 5.1	92 ± 8.6	92.6 ± 4.5	55.3 ± 5.7	85 ± 10.1	64 ± 10
Number of leaves	47 ± 11	37 ± 4.5	38 ± 2.5	14 ± 6.4	21 ± 2.6	18 ± 5.5
Root fresh weight (g)	3.1 ± 0.3	3.3 ± 0.1	3.4 ± 0.9	0.9 ± 0.8	2.7 ± 0.6	2.02 ± 0.6
Shoot fresh weight (g)	6.3 ± 0.8	4.3 ± 0.6	4.8 ± 0.6	1.1 ± 0.5	2.7 ± 0.3	1.8 ± 1.05
Leaf Area Index (LAI)						
Total LAI change (%)	366.89	174.69	300.13	− 49.62	− 26.92	− 30.96
Daily growth rate (%)	13.59	6.47	11.12	− 1.84	− 1.00	− 1.15
Physicochemical properties						
pH	7.2 ± 0.1	7.0 ± 0.03	7.6 ± 0.1	7.9 ± 0.1	8.1 ± 0.05	7.6 ± 0.1
EC (µS cm^{-1})	1195 ± 222.9	892 ± 75.8	866 ± 101.7	101 ± 2.9	277 ± 89.4	114 ± 20.1
Exchangeable cations (mmol kg^{-1})						
K^+	15.6 ± 1.3	33.1 ± 3	34.6 ± 5.2	14.2 ± 3.6	9.7 ± 4.9	6.1 ± 0.7
Mg^{2+}	69.7 ± 0.5	78.3 ± 8.4	71.9 ± 11.9	5.2 ± 1.2	6.5 ± 3.6	2.7 ± 0.2
Ca^{2+}	296.7 ± 44	257.1 ± 34	284.8 ± 23	31.3 ± 1.2	22.7 ± 12.5	4.9 ± 0.4
Na^+	5.8 ± 0.2	17.6 ± 2.4	17.1 ± 3.1	15.2 ± 4.1	9.6 ± 4.8	6.2 ± 0.7

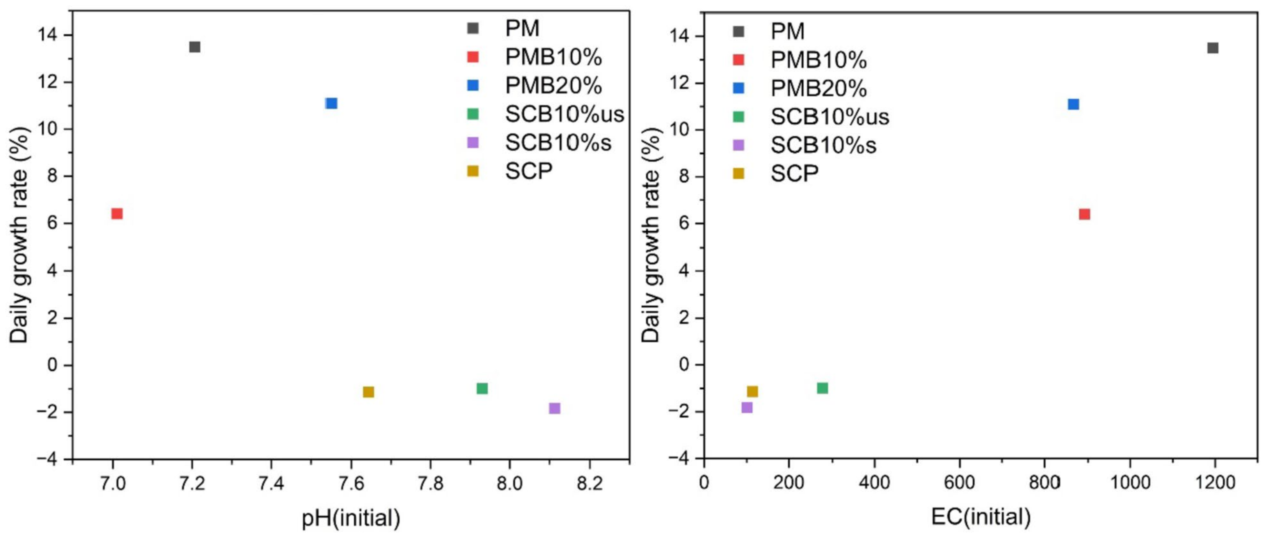


Fig. 1 The influence of pH and EC (μS cm^{-1}) of the growth mixes on daily growth rate (%) of basil

mix (Steiner and Harttung 2014). The biochar used in this analysis had a mesoporous structure with BET surface area of approximately 150 m^2 g^{-1} and pores in the range of 4 to 256 nm diameter (Adhikari et al. 2023a). Of the volumetric water uptake of 50%, more than 90% of water uptake was the intraparticle water, and around 5% was interparticle water. This implies that the plant available water mostly depends on structure, bulk density, sphericity or angularity of the biochar, compared to the inherent structure of the biochar. Optimized air space from 10% to 30%, total porosity 50% to 85%, water holding capacity 45–65%, and bulk density 0.4 g cm^{-3} were reported by Zulfiqar et al. (2019). Additionally, the nutrient retention and availability primarily depends on the feedstock of the biochar (Adhikari et al. 2024).

Biochar from olive mill waste in the study was found to be extremely saline in a 50% mix with coconut coir. This high percentage of mix was reported to have affected the growth of mastic and myrtle plants, and similar effects could be expected in the basil plants. Similar results were observed where application of 10% to 20% of biochar changed the pH of the system by ± 0.2 and a higher pH value of up to 8.1 in the growth mix with sand, coir and biochar soaked in Hoagland's (nutrient) solution (Fig. 1). However, these mixes are less saline compared to the potting mix as the EC is 6 times less than PM.

The biochar used in this study was made from mixed grass and woody feedstock. The biochar itself was alkaline in nature, pH 9.9. Therefore, it justifies that in the mix, when 20% of biochar was added, the pH of the potting mix-biochar mixture was increased. Other similar study by Nobile et al. (2020) has provided recommendations about the physico-chemical properties of the growth mix, where biochar with pH values between 5.3 and 6.5, EC ≤ 500 μS cm^{-1} and low density and high porosity is recommended, indicating that the physico-chemical properties of biochar has a significant effect on growth of basil. Biochar with high pH, ash and minerals content if applied in a higher rate may cause osmotic stress in plants, thus negatively impacting growth. Therefore, according to the plant type, the application rate of biochar should be optimised.

3.1.2 CEC of growth mixes

Potting mix showed a higher amounts of exchangeable calcium and magnesium, while the amounts of exchangeable potassium and sodium is similar in PM associated mixes as well as sand coir biochar mixes (Fig. 2). The number of exchangeable cations in the mix was evaluated before and after harvest to understand the influence of nutrients in the growth mix for the growth of basil.

When potting mix was replaced by 10% of biochar, the amount of exchangeable calcium increased, while the other nutrients such as K, Mg, and Na decreased in the mixes after a month, indicating that PM can break down and provide a source of calcium, while other nutrients are absorbed by the plant. Replacement with 20% biochar showed a similar trend as replacement with 10% biochar before and after harvest. However, the amount of exchangeable K, and Na was greater compared to only potting mix, indicating replacement of 10% to 20% of potting mix by biochar can increase the nutrient pool and its availability for plants in the growth media. Both replacement of potting mix by 10% and 20% biochar increased the amount of exchangeable potassium by more than double.

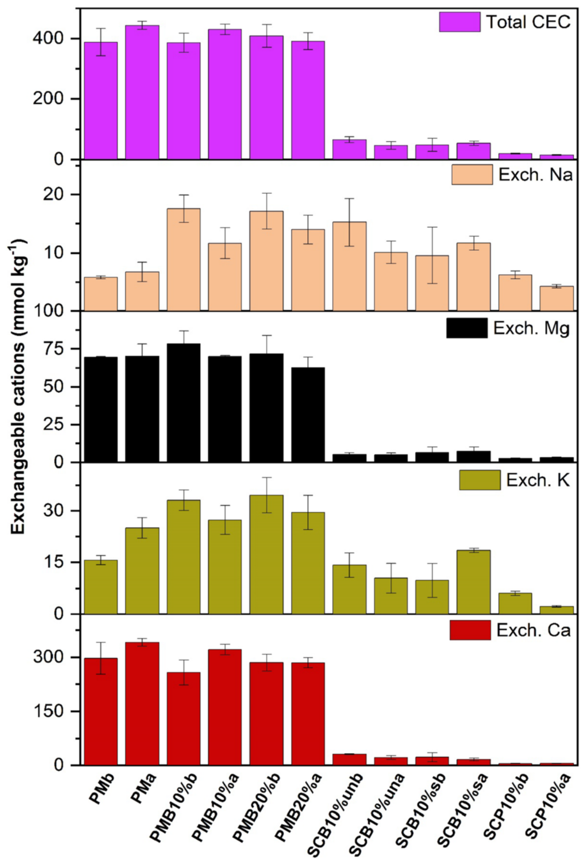


Fig. 2 Amount of exchangeable calcium (Ca), potassium (K), magnesium (Mg), sodium (Na) and total cation exchange capacity (CEC) in different growth mixes before planting basil and after harvesting it. Letters b and a at the end of mix indicate before planting and after harvest in all the growth mixes. For the potting mix, the number of all exchangeable cations increased after 1 month, indicating the high availability of nutrients. This might have been observed due to the breakdown of organic matter or fertilizers in the potting mix, releasing more nutrients into the exchangeable pool which would potentially be available to plants when required. As the study was limited to 1 month, there is a high chance that the basil plant did not have high nutrient requirement during the first month to grow

The mixes without potting mix, i.e. SCB10%s, SCB10%un and SCP showed significantly lower number of exchangeable cations compared to the ones with potting mix. The dominant nutrients in the PM are calcium and magnesium. Therefore, the SCB and SCP mixes were deficient in calcium and magnesium. However, they had comparable sodium and potassium. In the SCB10%s, which was soaked in the Hoagland's solution, the amount of exchangeable potassium and sodium increased after 1 month, indicating the nutrient pool for Na and K did not decline and the growth media acted as the slow-release source for these nutrients.

Based on the results, the growth media without PM can also be optimised for increased calcium and magnesium if the biochar is prepared from mixed wood and grass (straw) feedstock. A previous study from our research group (Adhikari et al. 2024) indicated that biochar feedstock can be optimised for enhanced nutrient availability. Current research by Bhengu et al. (2024) has optimised the nitrogen content for the growth of baby spinach, a popular salad ingredient in a commercial soilless growth media, indicating potential opportunities for optimised biochar as a growth media in horticultural applications.

3.2 Influence of growth media composition on plant morphology

The plant morphology was evaluated using 2 different approaches. The first approach was to assess the fresh root length and shoot height, number of leaves in the plant, and fresh and dry weight of the plants after 30 days. The second approach was to evaluate Leaf Area Index (LAI) by continuously monitoring the plants in the smart cabinets.

3.2.1 Analysis of plant growth

Firstly, the results showed that application of biochar in potting mix increased root length from 253 ± 25 mm in control to 265 ± 62 mm in PMB10% and 305 ± 21 mm in PMB20%. However, the shoot height was decreased by addition of biochar from 131 ± 5 mm in control to 92 ± 8.6 mm in PMB10% and 92.6 ± 4.5 mm in PMB20% (Fig. 4a). Similar root length was observed using the growth mix SCP, where 10% of perlite was mixed with 60% sand and 30% coconut coir. These growth media have been equally effective in root development compared to control. Perlite is porous and light in nature, and thus addition of perlite in the growth media is likely to increase the air and water availability in the roots. However, the finding that shoot development was not as effective as with other media indicates the lower cation exchange capacity of the growth media. Similar results were reported by Burdina and Priss (2016), indicating that the addition of up to 40% perlite with peat based substrate enhances biomass development as well as the ascorbic acid, and essential oils in the basil plant. Substrates like peat become compact with time, reducing the air and water availability; however, the addition of perlite helps to maintain the availability of air and water needed for further development. In addition, the growth mix, SCB10%s, which is a mixture of nutrient enriched biochar with sand and coconut coir showed a higher shoot height of basil compared to the addition of perlite or unsoaked biochar. This indicates that pre-treatment of biochar in the nutrient solution, or in other words, charging them with nutrients that the biochar can hold on to and may release later is beneficial for development of both root and shoot in basil plants when continuously monitored for 30 days. Similar results are shown by the research of Noroozi et al. (2023), where biochar amendment in soil enhanced the morphological properties such as seed yield and harvest index. Another study by Rathnayake et al. (2021) identified that root length of common garden cress, lettuce and tomato increased from 70% to 150% in the soilless growth media with 50% biochar and 50% peat substrate, attributing to the physico-chemical properties and porosity of the growth media. Despite addressing the nutritional inadequacies by enhanced root growth (Kaushal et al. 2024), we were not able to observe adequate shoot growth in basil (Fig. 3). Detailed photos of plants with replicates are provided in Appendix 1(A2). This might be due to the 30-day experimental period used in this study. SCP10% showed the longest roots which may be due to higher aeration resulting from increase in macropores (Kaushal et al. 2024) and overall porosity in the growth matrix; however, it also shows least number of leaves. Therefore, our results indicate that the surface morphology, porosity and physico-chemistry influence the air space and water retention in the growth mixes, thus influencing the growth of basil.

Secondly, regarding the growth of the leaves in the basil plant, ideal conditions were provided by potting mix, which was the control in this scenario. However, other growth mixes also provided considerable benefits (Fig. 4b). Among the other five growth mixes the maximum number of leaves were observed in PMB20%>PMB10%>SCB10%s>SCP> and SCB10%un. For basil plants, the developmental concern is the number of leaves they produce. After application of 10% and 20% biochar to the potting mix, the number of leaves was similar, 37±5 and 38±3, respectively. Therefore, as the similar development was observed in both growth mixes with 10% and 20% replacement of PM with biochar, the lower application rate is likely to be optimum to replace the PM. Similar results were observed by Nocentini et al. (2024), indicating moderate replacement of 10–20% peat based substrate by wood residue derived biochar pyrolyzed at 700 °C has positive implications to plant morphological growth. Additionally, biochar soaked in Hoagland's solution showed higher number of leaves, 21 ± 3 leaves, compared to the mixes with sand coir and perlite, which ranged from 14 to 18 leaves, indicating the nutrient charged biochar is likely to retain and deliver nutrients required for development of basil. The growth mixes with sand, coconut

Fig. 3 Comparison between root and shoot growth of plants in different growth media. PM = potting mix, PMB10% = Potting mix and 10% biochar, SCB10% = Sand, coir and biochar 10% soaked in nutrient solution and SCP10% = Sand, coir and perlite 10%

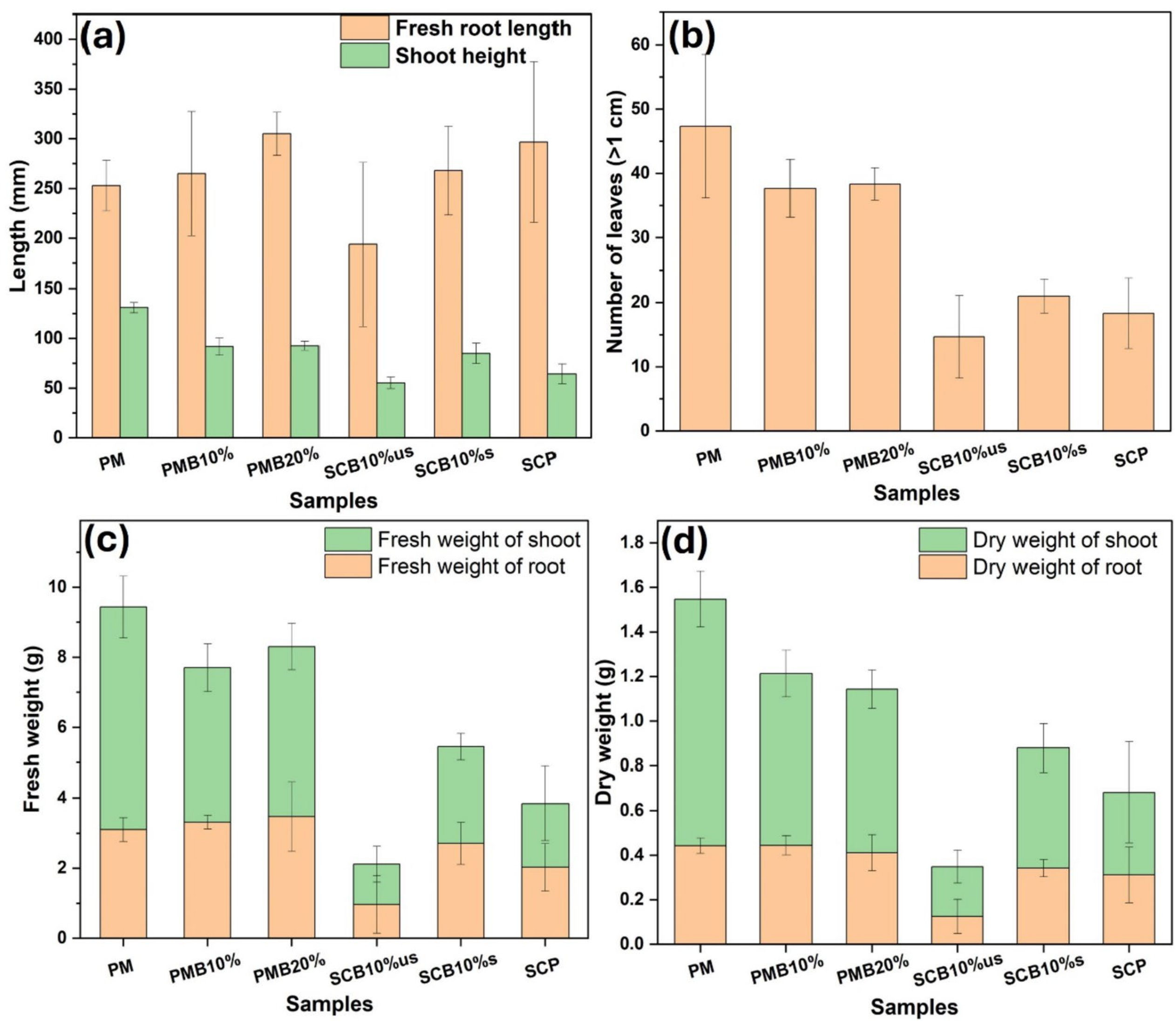


Fig. 4 Changes in root length (**a**), number of leaves (**b**), fresh weight of the plant (**c**) and dry weight of root and shoot (**d**) of basil plants grown in 6 different growth mixes

coir and biochar showed lowest number of leaves and least dry weight of leaves, indicating the effect of salinity of the growth media (Di Lonardo et al. 2017). These growth media with combination of sand, coir and biochar showed a higher electrical conductivity compared to the mixes with the potting mix and biochar.

Thirdly, similar results were observed for fresh and dry weight of roots and shoots, where PM contributed to best growth, followed by biochar mixed with the potting mix. However, the fresh weight (3.1±0.3 g) and dry weight (0.45±0.03 g) of roots of the plant grown in potting mix was equivalent to the fresh (3.3±0.1 g) and dry weight 0.45 ± 0.04 g of roots of the plant grown in the potting mix and biochar mixture (Fig. 4c, d). The weight of roots and shoots of the plants grown in the growth mix without potting mix in SCB10%s was similar (2.7±0.6 g), indicating the mixture of sand, coir and charged biochar had positive influence on root and shoot development of basil, similar to the potting mix.

The results revealed that the fresh weight of plants grown in the SCB10%s (2.6±2.7g) was three time higher compared to the plants grown in the mix SCB10%us, which is 0.9±0.8g. The SCB10%s was soaked in the nutrient solution and the SCB10%us was the biochar as it, (not treated with additional nutrient solution). Based on the

Table 3 Summary of Leaf Area Index (LAI) and growth rate of basil in different growth mixes

Growth parameter	PM (control)	PMB10%	PMB20%	SCB10%s	SCB10%un	SCP
Initial LAI (Pixel)	45,852.00	46,002.35	33,017.55	101,084.47	60,559.37	101,586.86
Final LAI (Pixel)	214,079.24	126,365.48	132,114.09	73,873.12	30,512.48	70,138.33
Total LAI change (%)	366.89	174.69	300.13	− 26.92	− 49.62	− 30.96
Daily growth rate (%)	13.59	6.47	11.12	− 1.00	− 1.84	− 1.15

fresh weight of plants, it is likely that biochar was able to hold nutrients on to it, and acts as a slow-release fertilizer, facilitating enhanced fresh weight of basil.

3.2.2 Leaf Area Index (LAI) monitoring

Table 3 presents the LAI measurements across all growth media treatments. The data show initial and final LAI values, total percentage change, and average daily growth rates for each treatment over the 30-day experimental period.

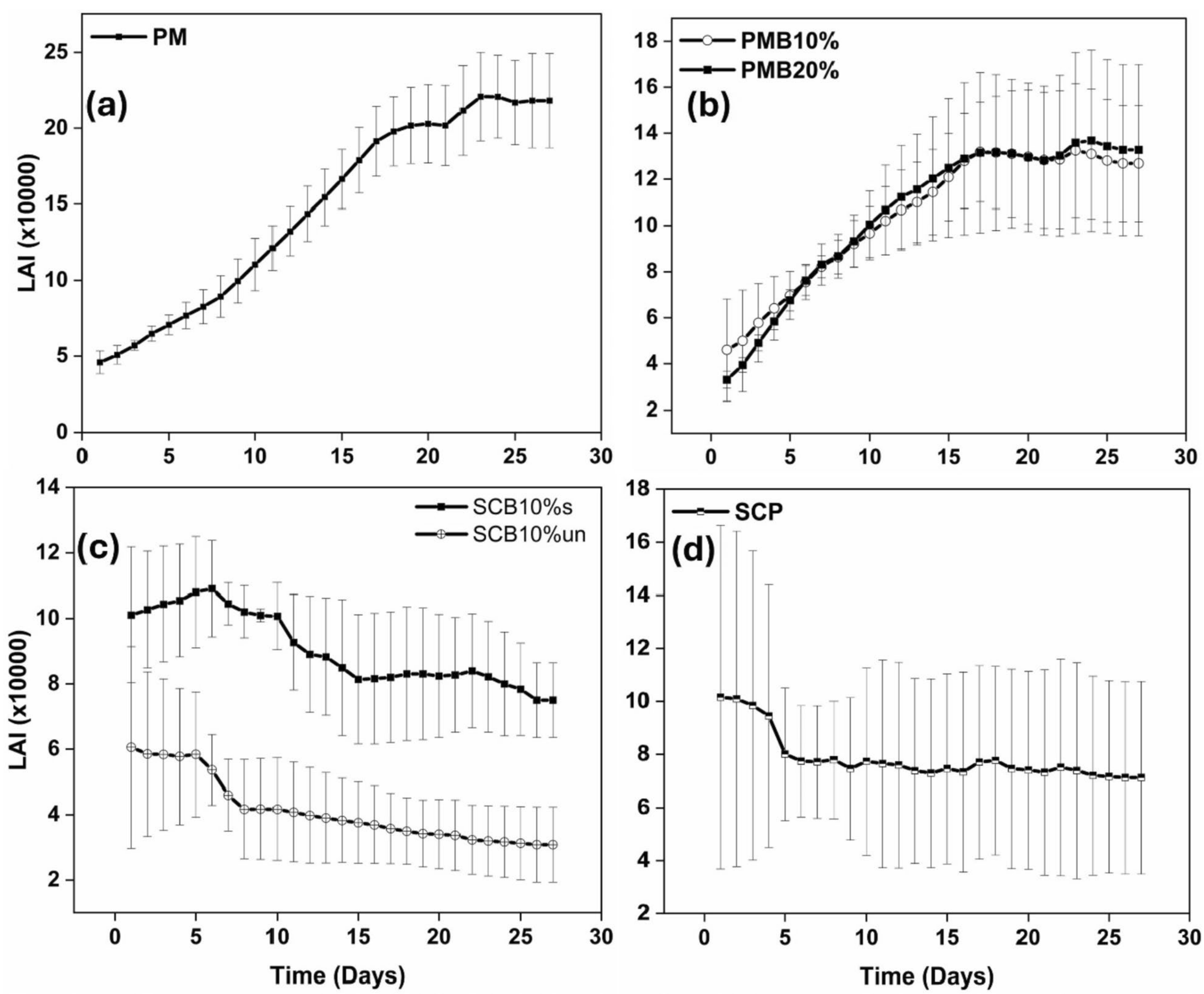


Fig. 5 Leaf area index (LAI) of plants in different growth media ± standard deviation from triplicates. **a** Refers potting mix, **b** refers to 10 and 20% mix of biochar in potting mix, **c** refers to 10% mix of soaked and unsoaked biochar in Hoagland's solution mixed with sanc and coconut coir and **d** refers to the mixture of sand coconut coir and perlite

The LAI results indicated that the potting mix substrates outperformed the sand substrates in terms of total leaf coverage. The LAI of plant grown in potting mix reached a maximum at 28 days (LAI of 214,079), with a daily growth rate of 13.6% and a daily LAI change of 366.9%. (Fig. 5a). This was closely followed by the PMB20% group with a total change of 300.1% and a daily growth rate of 11.1%. Finally, the PMB10% group only showed moderate growth, with a total change of 174.7% and a daily change of 6.5%. Detailed results are provided in appendix (Appendix 2).

While all potting mix mediums (PM, PMB10%, PMB20%) showed a net positive increase in size, the sand substrates (SCB10%un, SCB10%s, SCP) experienced a reduction in leaf area. The sand substrates showed a decline, with the SCB10%un displaying the most significant decline at a daily growth rate of −1.8%, reducing the overall size by −49.6 (Fig. 5b). The SCB10%s group saw an overall decline of −26.9% in size, with a growth rate of −1%. Results revealed different pattern in daily growth of plants in the mix with soaked and unsoaked biochar. There was a slight increase in growth for up to 5 days, and after that a sharp decline in growth was observed for 3 more days. After 8 days the growth was reduced and did not increase until 30 days in the plants grown in SCB10%un. However, in the mix with SCB10%s three points of decline was observed and the growth rate increased after each decline as well. The mix with 10% of biochar charged with nutrient solution showed up to three times higher growth compared to the biochar without soaking in nutrient solution (Fig. 5c). The SCP group also displayed a negative growth rate of −1.1%, reducing its side by −30.9% (Fig. 5d), with a sharp decline in first 5 days and a constant growth until 28 days.

The primary cause of this sharp decline in the size displayed in the sand samples can be attributed to the inability to maintain its initial leaves after transplanting. This, coupled with its inability to develop new growth, ultimately led to an overall decline in growth and a negative growth rate. These poor results documented in the sand mediums are hypothesised to be a result of the identical watering schedules used for both sand and potting mix mediums. More specifically, the sand appeared to retain too much water between waterings, leading to an oversaturation of the soil and poor plant growth. Additionally, the inclusion of small quantities of biochar in the sand substrates may have further increased water retention, exacerbating the the effect of sand.

3.2.3 Exchangeable nutrients in the growth mix

The results above show that PM provides best conditions for growth of basil. However, the mixes PMB10% and PMB20% as well as SCB10%s showed similar growth in relation to the potting mix. Therefore, based on the results from this research it can be stated that replacement of 10% biochar as a more sustainable growth media and use of sand, and coconut coir with nutrient charged biochar can provide similar benefits to using potting mix. However, understanding mechanisms influencing this growth is necessary. Therefore, the influence of exchangeable cations in the growth mix on daily growth rate of basil was investigated (Fig. 6).

Potting mix is abundant in exchangeable calcium, and magnesium but has lower exchangeable potassium and sodium. For a leafy plant like basil, the high priority nutrient is potassium, followed by magnesium, calcium and sodium. Potassium is crucial for leaf growth and water regulation in basil. Exchangeable potassium in SCB10%s was higher (9.57±4.8 mmol kg^{-1}) compared to potting mix (5.8±0.2 mmol kg^{-1}). Similarly, when the potting mix was replaced by 10% and 20% of biochar the exchangeable potassium content increased by more than 3 times.

Magnesium is also one of the crucial nutrients required for the growth of basil, which is important for photosynthesis and leaf development. The highest amount of exchangeable magnesium was available in PMB10% which was 78.3 ± 8.4 mmol kg^{-1} and was in the range of 60 to 70 mmol kg^{-1} in PM and biochar mix. However, the mixes with sand and coconut coir showed lower exchangeable magnesium of 5 to 6.5 mmol kg^{-1} and perlite showed least exchangeable magnesium (2.6 mmol kg^{-1}).

Similarly, the exchangeable calcium which influences the cell wall structure and strength of plants is the dominant cation in PM as well as PM and biochar mixes in the range of 296 ± 44.2 mmol kg^{-1}. However, in SCP10%, the exchangeable calcium was very low (4.8±0.3 mmol kg^{-1}).

Differences in the nutrient status might have influenced the growth of basil. This study was conducted for 30 days; therefore further growth was not documented. In addition, the number of exchangeable cations before and after harvest was evaluated and presented in the above section (Fig. 2). Graber et al. (2010) identified two mechanisms: (1) growth of microbial population such as rhizobacteria and fungi, and (2) stimulation of plant growth due to slow release of nutrients, which enhanced plant height and leaf size in tomato and pepper plant, but there were no differences in leaf nutrient content, and flower or fruit yield after application of wood derived biochar. Similar findings have been observed, where SCB10%s acted as slow release of potassium. SCB10%s showed highest growth compared to SCB10%un and SCP10%. The root length of 268 ± 44 mm, shoot height of 85 ± 10 mm, 21 ± 3 leaves greater than 1cm, and total fresh weight

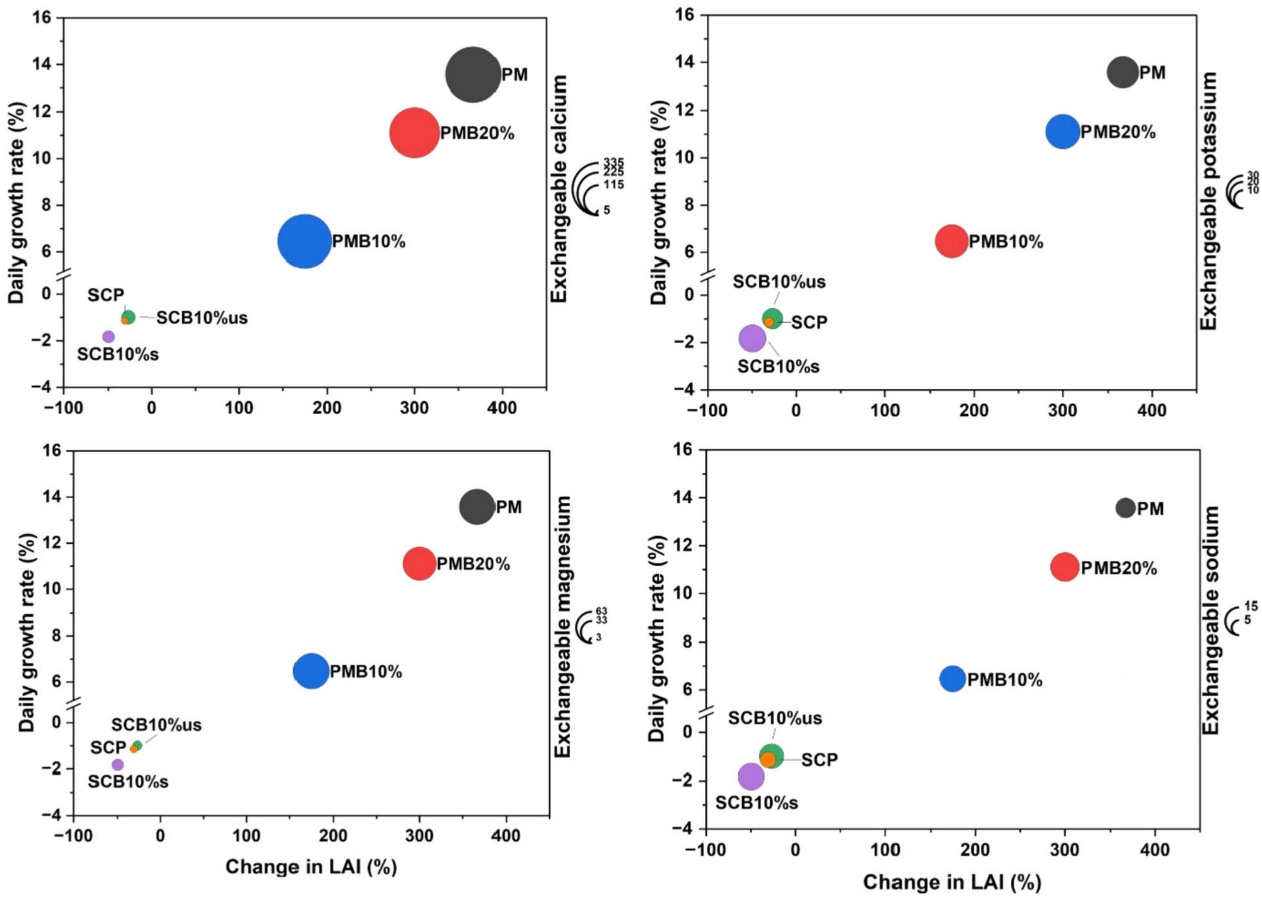


Fig. 6 Daily growth rate and leaf area index (LAI) Vs exchangeable cations present in the growth mixes

of plant 5.45 ± 0.8 g were observed for SCB10%s. Similar results have been observed by Zabaleta et al. (2024), who evaluated the effectiveness of almond shell biochar prepared at 450°C for the growth of arugula in different percentages with perlite as a soilless growth media. They identified that replacing 10% of perlite by the almond shell biochar improved the growth, while increasing the biochar content inhibited the growth of arugula plant.

Based on the results the mixes PMB10% would provide ideal conditions for growing basil. If opting for soilless growth media without potting mix, the SCB10%s provided ideal conditions for growth of basil, but required some optimisation regarding nutrient and pH.

3.2.4 Na and K saturation in the growth mixes

The saturation of base cations of the mix was analysed before and after the planting of basil. It was observed that PM had the lowest amount of exchangeable Na and K, which increased after the replacement of 10 and 20% of biochar. This indicates that biochar is an effective source of Na and K for plant growth. Detailed results are provided in Fig. 1 of Appendix 2. Excessive Na in the growth media is likely to cause Na sensitivity in the plants (Kingston et al. 2020). Therefore, an understanding of Na and K in the growth media and its influence in plant biomass development is crucial.

Our results revealed that replacing 10% of potting mix by biochar was optimum for Na and K. K and Na saturation increased by more than double after adding 10% and 20% biochar in the potting mix (Fig. 1, Appendix 2). Similar results were reported by Danish et al. (2024), using cabbage waste biochar prepared at 360 °C, with sandy soil and potting mix for basil growth. They identified that 6% replacement of potting mix by biochar in the growth mix showed higher potassium retention, as well as enhanced leaf chlorophyll, and water content, compared to only potting mix. Biochar plays an important role in nutrient delivery in the growth mixes, and it provides opportunities to optimise the nutrient concentration in the mixes facilitating enhanced plant growth. Biochar used in this study was derived from mixed grass and woody biomass, but the nutrient content in the biomass primarily depends on the feedstock (Adhikari et al. 2024). It was reported that in a peat, biochar growth media mixture up to 70% of peat could be replaced by a mixed hardwood biochar without any negative effects on plant biomass (Yu et al. 2019) based on phytotoxicity, growth index and soil pant analyses and development tests. However, biochar properties vary widely depending on the feedstock, which needs to be considered before optimisation of growth media using biochar.

The K/Na ratio for all the growth mixes was observed to be less than 5. Detailed data is provided in (Table 3, Appendix 2). The K/Na ratio provides idea about the movement of sodium in the growth media, and if it inhibits the movement of potassium. Higher the K/Na ratio, higher is the resistance to salinity (Mehdizadeh et al. 2019). The K/Na ratio value of the growth media correlates with the growth of basil. Highest growth was observed in PM, followed by PMB10% and PMB20%, and lowest growth was observed in SCP10%, and thus similar results are observed in the K/Na ratio.

3.2.5 Usage and availability of K by basil in the growth mix

The amount of exchangeable K in the mix before and after planting basil was identified. Results showed that basil plants grown in PMB10%, PMB20% and SCP10% used potassium from the growth mix for the plant growth. The K in the growth mix in these three mixes reduced after harvesting the plant, compared to the K content before planting. Detailed results are provided in Table 3, Appendix 2.

Approximately 25% of K was used by basil in PMB10%, indicating that Na in biochar did not interfere with movement of K and facilitated plant uptake and growth. Mehdizadeh et al. (2019) reported that mulberry wood biochar helps to reduce the salinity stress in plants by reducing the absorption of Na. Similar results were found in our study where absorption of Na decreased from 40% in PMB10% to 14% in PMB20%. Increase in biochar concentration in the growth mix decreased the sodium absorption by 26%.

Application of perlite showed significant usage of K (around 50%), likely hindering growth of basil. This indicates that the increased level of K absorption and decreased Na absorption were likely due to the change in growth media such as biochar or perlite. Therefore, the results provide insights into growth media type and content, and its relationships with salinity and plant growth, identifying opportunities for further investigation on interactions with other media components are recommended for future research.

3.3 Co-benefits of biochar for carbon storage

In addition to benefits to soil nutrient profile, as well as plant root and shoot development, replacement of 10% potting mix by biochar as in the PMB10% is beneficial from environmental perspective as well. Our results are confirmed by a current study (Chrysargyris et al. 2024), which reported that peat-based substrate can be partially replaced by 10% of wood derived biochar produced at 700 °C in pot growth of *Antirrhinum majus* plant for co-benefits to plant growth and circular economy. Carbon present in biochar is stable for more than 100 years, and the decomposition is only assumed to be around 10% every 3 years (Joseph et al. 2021). However, in the potting mix, made from different organic material such as litter, pine bark, or compost, it is estimated to decompose by 90% every year, generating CO_2, CH_4 and other greenhouse gases.

Potting mix derived from pine bark has around 52% carbon dry basis (Hunter et al. 2011). However, biochar is a carbon matrix which has more than 75% of carbon present in it (Adhikari et al. 2023b). Carbon sequestration (CO_2eq per year) of the two was estimated using secondary data from literature (Appendix 3), which showed that the PMB10% sequestered more CO_2 compared to PM alone. Use of 25 L of pine bark derived potting mix produces around 16 kg CO_2eq per year assuming it decomposes by 90% within a year (Joseph et al. 2021). However, replacement of 10% of the potting mix (2.5 L) by biochar provides benefits to plants as well as sequestration of 2 kg CO_2eq per year. The actual carbon sequestration potential of biochar depends on the feedstock used, carbon stability of biochar itself, and the production technology used. However, this conservative sequestration estimate indicates that replacement of pine bark with biochar in potting mix reduces GHG emissions, by providing a more durable growing medium that does not fully decompose each year releasing CO_2.

Addition of biochar to growth media has additional co-benefits to nutrient and water availability by providing a stable carbon matrix that does not decompose like potting mix and coir. Substituting some organics part of a growth medium with biochar can thus avoid GHG emissions, store carbon and potentially be more cost-effective. This can he successfully quantified if the same growth medium is used over the years in container plant production system in the nurseries at a large scale. These benefits can be harvested in a large scale with significant technical, economical and societal readiness for this technology. However, some challenges such as the need of larger financial return for businesses, underexplored potential such as carbon credits from biochar use and lack of public awareness (Chopra et al. 2024) still hinder the use of biochar in different parts of the world.

4 Conclusion and recommendations

This study evaluated the effectiveness of sustainable growth media on basil growth compared to traditional potting mix, within a protected cropping environment that was enhanced by IoT monitoring. Our findings emphasize the importance of optimizing basil growth in soilless media containing biochar or coconut coir. However, research on nutrient management and media composition in these systems remains limited. Key results indicate that high electrical conductivity (EC) and low pH can hinder growth, with optimal conditions observed around pH 7.5 and EC up to 1200 µS cm^{-1}. Replacement of 10% potting mix with biochar increased root length and enhanced nutrient exchange, especially Na and K. Nutrient-enriched biochar provided three times the plant weight compared to non-soaked biochar, supporting its role as a nutrient-holding matrix for gradual release. Growth rates for 10% and 20% biochar showed similar trends, making 10% an efficient replacement rate. This research provides novel and timely insights into importance of continuous monitoring with integration of IoT for real-time plant growth assessment, enhancing sustainable horticulture practices in line with sustainability and circular economy goals. For future research, it is recommended to further investigate long-term nutrient dynamics in biochar-amended growth media, with different plant species and varying environmental conditions. Further studies are also recommended for biochar as a possible perlite replacement in growth media, with opportunities to provide aeration and drainage or moisture retention, while also sequestering carbon and providing nutrient benefits. This could provide more comprehensive insights into the effectiveness of biochar as a growth medium.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s42773-025-00480-0.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Acknowledgements

The authors would like to thank Green Man Char, Melbourne, Australia for providing the biochar samples for the research. We also thank Earth Systems engineers, who designed and developed the pyrolysis technology to produce Green Man Char, for their ongoing interest in biochar applications research. The authors would also like to thank the two anonymous reviewers for their constructive comments for improvement of this manuscript.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Sirjana Adhikari. The first draft of the manuscript was written by Sirjana Adhikari, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding

This research was supported by a Seed Grant from Centre of Sustainable Bioproducts, Deakin University.

Data availability

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

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Received: 16 December 2024 Revised: 23 May 2025 Accepted: 27 May 2025
Published online: 03 July 2025

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